Improved Heuristic Drift Elimination (iHDE) for Pedestrian Navigation in Complex Buildings

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Abstract—The main problem of Pedestrian Dead-Reckoning (PDR) using only a body-attached IMU is the accumulation of heading errors. The heading provided by magnetometers in indoor buildings is in general not reliable. Recently, a new method was proposed called Heuristic Drift Elimination (HDE) that minimizes the heading error when navigating in buildings. It assumes that the majority of buildings have their corridors parallel to each other, or they intersect at right angles, and consequently most of the time the person walks along a straight path with a heading constrained to one of four possible directions. In this paper we study the performance of HDE-based methods in complex buildings, i.e. with pathways also oriented at 45°, long curved corridors, and wide areas where non-oriented motion is possible. We explain how the performance of the original HDE method can be deteriorated in complex buildings. We also propose an improved HDE method called iHDE, that is implemented over a PDR framework that uses foot-mounted inertial navigation with an Extended Kalman Filter (EKF). The EKF is fed with the iHDE-estimated orientation error, as well as the confidence over that correction. We experimentally evaluated the performance of the proposed iHDE-based PDR method, comparing it with the original HDE implementation. Results show that both methods perform very well in ideal orthogonal narrow-corridor buildings, and iHDE outperforms HDE for non-ideal trajectories (e.g. curved paths).

I. INTRODUCTION

The main problem of Pedestrian Dead-Reckoning (PDR) using only a body-attached IMU (Inertial Measurement Unit) is the accumulation of heading errors. The heading provided by magnetometers in indoor buildings is in general not reliable. Recently, a new method was proposed by Borenstein and Ojeda [1] called Heuristic Drift Elimination (HDE) that minimizes the heading error when navigating in buildings. It assumes that the majority of buildings have dominant directions defined by the orientation of their corridors; consequently a person walks most of the time along straight-line paths parallel to these dominant directions. Abdulrahim et al. [2] exploit the same building’s dominant directions assumption, but they implement the HDE idea in a totally different way.

The implementation in [1] uses a feedback control loop at the output of a vertically-aligned gyroscope. In the loop there is an integration stage to obtain the heading angle from the gyroscopic angular rate, and then this angle is compared to one of the main building orientations. The heading error

![Fig. 1. Building with a complex layout: The Engineering School of the University of Alcalá-de-Henares (UAH) in Spain.](image-url)
II. HDE: BENEFITS AND LIMITATIONS

A. Benefits

HDE methods estimate the non-deterministic slow-variant bias of the gyro’s angular rate. Therefore, they make the heading error to be observable. In fact the heading observability is almost as good as if a digital compass were used (assuming no magnetic disturbances). An HDE-based PDR solution basically eliminates the error in heading, and consequently, it reduces the positioning error. For example in [1] a 0.33% error of the Total Traveled Distance (TTD) is obtained, and in [2] the reported error is just 0.1% of the TTD.

Fig. 2 shows a PDR trajectory estimation example using HDE in an “ideal” floor that includes narrow long corridors at 0, 45° and 90° orientations. If the least angular difference between the dominant directions in a building is denoted by $\Delta$, then this difference is 45° for the building under test in this paper ($\Delta = 45^\circ$). In Fig. 2 is also included the non-HDE aided solution (IEZ) that is dominated by the uncorrected gyro drift in heading. As can be seen, HDE is an extraordinary method to navigate indoors.

B. Limitations

HDE uses a progressive correction of the gyro bias in order to obtain a robust operation even under temporal paths along non-ideal paths (curved or straight paths out of the dominant directions). If walking more than 30-60 seconds along non-ideal paths, then HDE can deteriorate the navigation solution as Borenstein states [1]. In Fig. 3 it is graphically shown the damaging actions of HDE for two non-ideal paths. The deformation of the true trajectory is progressive, not too severe, but causes a slight error in positioning and heading. This progressive error accumulation, could in principle cause the estimated trajectory to match a wrong dominant direction, although it is unlikely if $\Delta \geq 45^\circ$ and the non-ideal paths are not too long.

III. THE PROPOSED iHDE METHOD

A. The IEZ Framework for pedestrian navigation

We use the foot-mounted IMU-based PDR algorithm proposed by Foxlin [3] and later refined by Jiménez et al. [4], named IEZ. This approach uses Zero Velocity Update corrections (ZUPT) every time the foot is motion-less (stance phase), as well as, Zero Angular Rate Updates (ZARU), when the person does not walk (still). It uses an Extended Kalman Filter (EKF) that works with a 15-element error state vector: $X = [\delta A_t, \delta \omega_b, \delta P_o, \delta V_e, \delta a_b]$. This vector contains the estimated bias of accelerometers and gyroscopes ($\delta a_b$ y $\delta \omega_b$, respectively), as well as, the 3D errors in attitude ($\delta A_t$), position ($\delta P_o$), and velocity ($\delta V_e$).

Fig. 4 represents a block diagram of the complete IEZ PDR method (white color boxes), plus the proposed iHDE implementation (light-gray color blocks) that includes a “movement analysis” processing block, and an “error in heading” estimation block.

B. Movement Analysis in iHDE

Our movement analysis block, analyzes the stride direction of the person when walking, the length of this stride and decides if the trajectory is straight. This information is used to design some attenuators that will restrict the corrections of HDE to only some sections of the path. They are needed...
to estimate the heading error and the confidence on that estimation.

1) Stride Direction: The direction of movement of the pedestrian when walking is:

$$\theta_S(k) = \arctan\left(\frac{P_{0_y}^k - P_{0_y}^{k-1}}{P_{0_x}^k - P_{0_x}^{k-1}}\right),$$

where \(k\) is the index of the \(k\)-th step.

2) Stride Length (SL): Knowing the Stride Length (SL),

$$SL(k) = \sqrt{(P_{0_x}^k - P_{0_x}^{k-1})^2 + (P_{0_y}^k - P_{0_y}^{k-1})^2},$$

a Step Size (SS) binary attenuator is computed as:

$$SS(k) = \begin{cases} 1 & SL(k) > Th_{SS} \\ 0 & \text{Otherwise} \end{cases},$$

which will be later used to reject HDE corrections when walking with short steps. A threshold for the SL of 1 meter (\(Th_{SS}=1\) m) is used.

3) Straight Line Path (SLP): We decided to require at least five user strides with similar orientation in order to classify a trajectory as straight. We compute a binary Straight-Line Path (SLP) parameter as:

$$SLP(k) = \begin{cases} 1 & \max(|\theta_S(j) - \text{mean}(\theta_S(j))|) < Th_{SL} \\ 0 & \text{Otherwise} \end{cases},$$

where \(Th_{SL}\) is an angular threshold. SLP is used to deactivate the perturbing HDE corrections at curved paths.

### C. Estimating the error in heading in iHDE

The error in heading is computed as a direct subtraction between the stride direction \(\theta_S(k)\) at step \(k\), and the closest dominant direction of the building \(\theta_b(k)\), as:

$$\delta \theta(k) = \theta_S(k) - \theta_b(k).$$

This is the error in heading that is fed into the EKF for a subsequent heading correction and an internal gyro bias estimation.

### D. Confidence of the error in heading

We define the following expression for the standard deviation of the error in heading (\(\sigma_{\delta \theta}\)), so as to make the iHDE heading correction adaptive with each kind of motion:

$$\sigma_{\delta \theta}(k) = \frac{\sigma_{HDE}}{SLP \cdot SS \cdot e^{-5\delta \theta(k)/\Delta}}.$$  \hspace{1cm} (6)

The value of \(\sigma_{HDE}\) is 0.1 radians. The exponential term is used to limit the correction from straight paths not too aligned with the building’s dominant directions. Note that only straight well-aligned paths are basically used in iHDE. This contrasts with the original HDE method that always applies corrections, even in curved trajectories, if steps are long enough.

### IV. EXPERIMENTAL EVALUATION

For the evaluation of the proposed iHDE method, and for comparing it to the IEZ and HDE methods, we use both, synthetically generated IMU signal with a ground-truth, and also real experiments performed at a building using a foot mounted IMU.

A. Evaluation using a synthetically generated IMU signal with a ground-truth

We have employed several synthetically-generated IMU signals using the methodology proposed in [5]. Each generated IMU signal has a ground-truth of the position (as well as attitude and velocity) for every sample in the simulated trajectory. The ideal IMU signal sampled at 100 Hz, was contaminated with a known constant bias at the gyroscopes (0.01, 0.006 and 0.003 rad/s for axes x, y, and z, respectively).

All trajectories generated have an initial and final interval where the IMU is motionless, in particular the simulation interval (first 1000 samples) allows the system to start moving, and also just after ending the trajectory for another 10 seconds.

A square trajectory repeated twice was generated as an “easy” one satisfying very well the HDE assumptions (moving along two principal directions: North-South or East-West; i.e. \(\Delta=90^\circ\)). In this case the IEZ method is expected to accumulate drift in heading, but HDE and iHDE should clearly get advantage of the dominant directions corrections to eliminate the drift. Results are shown in Fig. 5.

We observe in Fig. 5a that the IEZ solution has some drift in yaw, as expected, however this drift is not so damaging since the ZARU correction of IEZ during the initial 10 seconds interval (first 1000 samples) allows the system to...
Fig. 5. Evaluation of algorithms using a synthetically-generated IMU signal that corresponds to a square trajectory repeated twice. a) Estimated trajectory using IEZ method (left), and the estimation of the biases of the 3-axes gyroscope (right); b) The same as before for HDE method; c) The same as before for iHDE method.
partiallly estimate the gyro biases. During the motion there is no observability of yaw angle, so estimated biases do not improve, although the uncertainty in the covariance matrices of estimates grows. The final still phase achieves the correct estimation of gyro biases. For the HDE method we observe in Fig. 5b that yaw is observable and consequently the bias of gyroscopes. After 100 s of walk (10,000 samples) biases are well estimated. The 8 spikes in the bias plot corresponds to the 8 turns that slightly perturbs the estimations. The iHDE method performs similarly to HDE as can be seen in Fig. 5c, but in this case no perturbations appear since during turns no corrections are applied. For this “ideal” type of trajectories both HDE and iHDE method perform quite well eliminating the drift in heading.

A more challenging trajectory for HDE is evaluated as presented in Fig. 6. This trajectory consists of two straight line segments aligned with one of the dominant directions (west-east) at the beginning and end sections, and in the middle a straight-line segment 30° degrees oblique from the dominant direction. The bias convergence in Fig. 6a for IEZ is similar to the case presented before in Fig. 7a. The middle segment is not correctly processed by HDE method, neither in the position estimation nor in the bias estimation. In fact the bias is wrongly estimated during this oblique path (samples from 2800 to 4400). When the path is again aligned with the dominant direction (samples 4400 to 6100) the bias is progressively recovered to the true value. The performance of iHDE is improved simply by ignoring the yaw corrections during the non-aligned sections of walk, under this case it basically uses the previously computed biases.

Another challenging trajectory for HDE is evaluated as presented in Fig. 7. This trajectory consists of two straight line segments aligned with one of the dominant directions (west-east) at the beginning and end sections, and in the middle two iterations of a circular trajectory having a radius of 10 meters. The IEZ performs as usual, it is basically not dependent on the kind of trajectory, as it is observed in Fig. 7a. The degradation expected for HDE can be visualized in Fig. 7b, there is a deformation of the circular path shape and an error in the heading. This is caused by the alternative corrections in yaw on each two dominant directions (horizontal and vertical). The eight peaks in the bias estimations during the 2 circular paths corresponds to the 4 damaging correction along the directions in a single cycle: North-South, West-East, South-North, East-West. iHDE on the contrary deactivates corrections during the circular path and consequently only accumulates a drift in heading similar to that of IEZ, but the positioning and heading error is corrected when walking again along a straight path at the end of the trajectory (see Fig. 7c).

B. Evaluation using Real IMU signals recorded in a complex building

Several tests were performed using a foot-mounted IMU (XSens Inc.) at the building shown in Fig. 1 (∆ =45°).

1) Wide slightly-curved corridors: In the first floor of this building, there are wide curved corridors (see Fig.8a). We tested the HDE and the proposed iHDE algorithms in these challenging conditions. The positioning results for a closed 460-meters-long path is shown in Fig.8b and c. The damaging action of HDE is perceived mainly in the curved path in the east wing. iHDE basically does not apply corrections on curves and achieves a slightly lower positioning error than HDE.

2) Circular Paths: Other results for circular paths are presented in Fig. 9. The damaging effect of HDE causes a position and orientation error when finishing the circular loops (e.g. after the 4 loops in Fig. 9 just before returning straight to the starting point). Other tests performed confirmed improvements of the iHDE method over the HDE for routes including difficult trajectories (improvements of about 0.2% of TTD). In more “ideal” floors having long narrow corridors (like the third floor in Fig.2), the performance of HDE and iHDE is quite similar, as expected.

V. CONCLUSION

We have analyzed the limitations of the HDE method, proposed a improved version (iHDE), and tested both in challenging buildings. We confirm that the heuristic that uses the dominant’s directions of the building is an extraordinary method to implement practical PDR indoor navigation solutions (with none or a minimum infrastructure), and it is a great alternative to compass-based navigation when magnetic disturbances are significant.

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Fig. 6. Evaluation of algorithms using a synthetically-generated IMU signal that corresponds to two straight line segments aligned with one of the dominant directions and another 30° oblique segment. a) Estimated trajectory using IEZ method (left), and the estimation of the biases of the 3-axes gyroscope (right); b) The same as before for HDE method; c) The same as before for iHDE method.
Fig. 7. Evaluation of algorithms using a synthetically-generated IMU signal that corresponds to two straight line segments aligned with one of the dominant directions and 2 circular paths in between having a radius of 10 meters. a) Estimated trajectory using IEZ method (left), and the estimation of the biases of the 3-axes gyroscope (right); b) The same as before for HDE method; c) The same as before for iHDE method.
Fig. 8. Tests in a floor with wide and curved corridors. a) Photo of the corridor, b) Estimation with HDE, c) Estimation with iHDE. The black small circles in the path mark the HDE or iHDE heading corrections. The size of these circles is inversely proportional to \( \sigma_{\delta \theta} \). HDE is making corrections all the time with a constant \( \sigma_{\delta \theta} = \sigma_{\text{max}}/SS \), however iHDE corrects adaptively, mainly at well-aligned straight-line segments, using eq. 6.

Fig. 9. Test walking around a circular path 4 times (the starting and final path is straight at a 45° dominant direction). a) HDE estimation, b) iHDE estimation. The total route length is 146 m.